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# Heat Integrated Distillation System Design

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Distillation is the largest single energy consumer in the chemical process industries. However, distillation does not consume energy but degrades the heat input to the reboiler that is subsequently rejected in the condenser. The most effective way to reduce the energy consumption of distillation is by effective heat integration. However, the distillation design and operation must be considered simultaneously with its heat integration. For single distillation columns it is straightforward to identify appropriate heat integration opportunities. For complex distillation systems, the most appropriate combination of distillation system design and operation and heat integration are far from straightforward. The whole separation system together with its heat integration and utility system must be considered simultaneously. This presentation will explain new approaches to be design of heat integrated distillation systems. Examples will be developed from crude oil distillation and from low-temperature separation in chemicals production.

## 1. Background

The design and retrofit of heat integrated distillation systems has been the subject of much research in process engineering in the last two decades. The traditional approach to develop a heat integrated distillation system design has been to decompose the problem into two sub-problems. First, the distillation structure is considered, whether this be new design or retrofit. Second, the heat integration of the individual columns is manipulated to reduce costs. However, there are significant interactions between the distillation design and the heat integration. Table 1 presents a summary of the variation of distillation column design parameters with operating conditions. It is clear from Table 1 that as the pressure and feed condition of the distillation is varied, then not only is the design of the distillation column itself changed, but also its heat integration characteristics. Added to this, there are significant interactions between the distillation columns. For example, if the bottoms of an upstream column feeds a downstream column with a saturated liquid, and the pressure of the downstream column is decreased in an optimisation, then the feed to the downstream column changes from being a saturated liquid to being partially vaporised. This in turn changes the design and heat integration characteristics of the downstream column.

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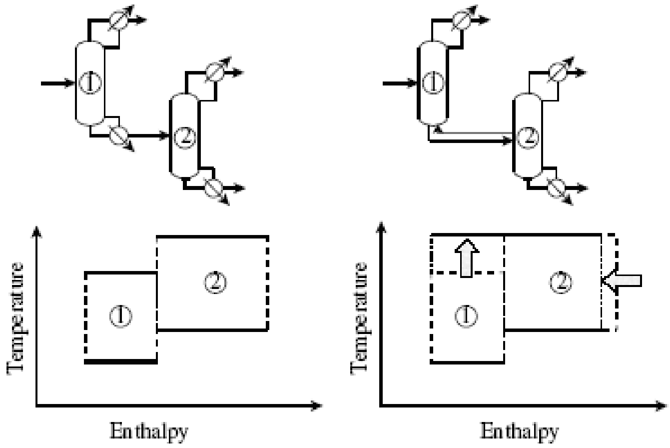
*Table 1 Variation of distillation column design parameters with operating conditions*

| | Pressure | Feed condition |
|---|---|---|
| Condenser temperature | ✓ | |
| Reboiler temperature | ✓ | ✓ |
| Condenser duty | ✓ | ✓ |
| Reboiler duty | ✓ | ✓ |
| Feed heater temperature | ✓ | ✓ |
| Feed heater duty | ✓ | ✓ |
| Column diameter | ✓ | ✓ |
| Number of stages | ✓ | ✓ |
| Product-stream temperature | ✓ | |



(a) Indirect distillation sequence (b) Thermally coupled indirect sequence.

*Figure 1: Introducing complex column arrangements changes both the loads on the system and a level*

The discussion so far has concentrated on distillation column designs that are conventional. This would be characterised by a column with a single feed, two products and having a reboiler and condenser. Many complex column arrangements can be introduced into the distillation system design. These include side strippers, side rectifiers, pre-fractionators, and dividing wall (partition) columns. These options effectively carry the function of two conventional columns and produce three products. However, the heat integration characteristics changed fundamentally. This is illustrated in Figure 1, which shows a direct sequence of two simple distillation columns (Smith, 2005). As the column configuration is changed from two simple columns to a complex column arrangement, the heat duty on the system decreases, but more heat needs to be added at extreme temperatures. Similar problems exist with the other forms of complex column. Generally, complex column arrangements use less energy, but require proportionally more heating and cooling at more extreme temperatures. Reducing the thermal load benefits heat integration, but more extreme temperatures make heat integration more difficult.

Thus, the problem of heat integrated distillation system design is a question of choosing the most appropriate order in which to make the separation, choosing the most appropriate column design, column pressure and feed condition to minimize the overall energy consumption through heat integration.

Consider first one of the classic problems of heat integrated distillation system design, that of crude oil distillation.

## 2. Crude Oil Distillation

Crude oil distillation processes consume energy intensively, and rank second for energy consumption in the refining industry, after the catalytic reforming processes. A relatively small energy saving opportunity in the distillation process will have an impressive economic impact. Figure 2 shows a conventional crude oil distillation process with an atmospheric and vacuum tower. The preheat train is shown as a simple schematic before and after the desalter. The common pumparounds and product streams provide heating for the incoming crude oil in what is typically a very complex heat recovery arrangement. In many existing refineries, these systems were designed many years ago when energy prices were relatively low. As energy became more expensive, there appeared a great incentive to redesign the existing heat exchanger network (HEN) to identify more heat recovery opportunities. Many other crude oil distillation arrangements than the one shown in Figure 2 are possible. However, all share the common feature of a complex heat exchanger network that interacts strongly with the distillation design and operation.

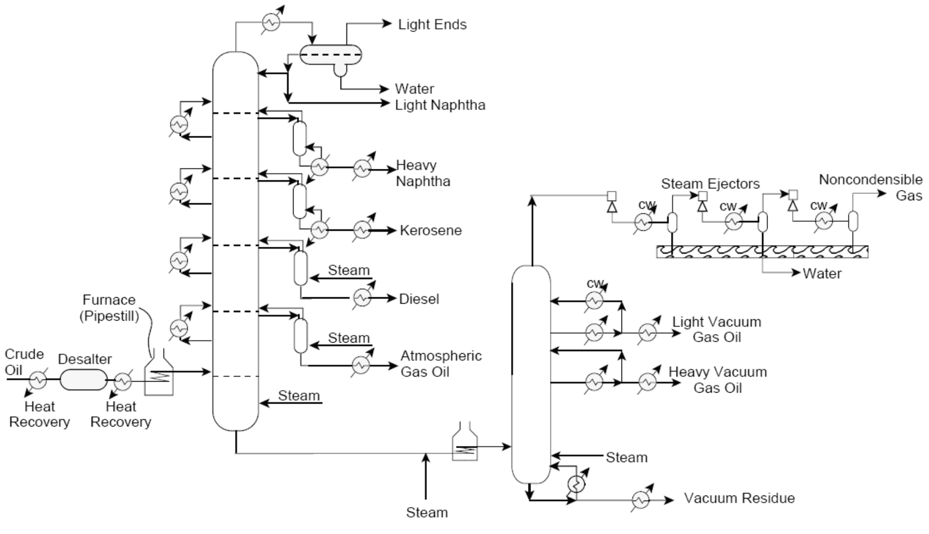


*Figure 2: Conventional crude oil distillation*

There are many issues to consider in designing complex crude oil distillation columns, such as: choice of the stripping steam flow rates, feed preheating temperatures and reflux ratios for the specified separation; appropriate places of locating pump-arounds or pump-backs and how to operate them (flow rate and temperature-drop), *etc* (Chen, 2008). The cooling and heating duties of the preheat train are determined by the distillation columns. How to operate the distillation columns is of prime importance, which not only affects the separation performance itself but also determines the energy consumption of the system. Optimisation is necessary to exploit these design issues for performance enhancement. To optimise operating conditions of the distillation columns, robust and computationally efficient models are necessary. Simplified models of distillation columns for the design and analysis of crude oil distillation system have been developed (Chen, 2008, Gadalla et al., 2003). The models include refining product specifications and consider the effect of different pump-around locations on separation in atmospheric units.

There are strong interactions between the distillation columns and the heat recovery system. For example, if the flow rate or temperature drop of one of the pump-arounds is increased, there will be more heat to recover in the preheat train, which in turn may decrease the furnace duty for preheating the crude oil. The change in the pump-around operation improves the potential of heat recovery with the atmospheric column, but at the same time reduces the internal reflux on the stages above the draw, so less separation takes place in the distillation column. If the flow of stripping steam to the bottom of the column is decreased, the temperature of the bottom product increases and the heat that can be recovered from this product increases.

Thus, the energy demand of the crude oil distillation system is determined not only by the design of the distillation columns but also by the design of the heat recovery system. For system design, there is a need to consider the interactions between the distillation columns and the HEN and to account for the interactions accurately. Considering the complexity of the heat-integrated distillation system, an optimisation-based approach is proposed to exploit the degrees of freedom in the design of fixed distillation configurations.

This approach incorporates the simplified distillation models and the heat exchanger network models. The methodology is applicable to both grassroots and retrofit design of heat-integrated crude oil distillation systems, and to different design objectives, such as energy demand reduction, profit improvement, *etc*. Product specification constraints are taken into account in the methodology, together with other practical constraints, such as the capacity of the existing columns in retrofit designs, forbidden matches in the heat exchanger network topology, maximum number of topology modifications in retrofit designs, *etc*., to make sure that the final design is practicable, industrially acceptable and applicable. The operating conditions and structures of both the distillation columns (e.g. pump-around location) and the heat exchanger network are varied in the optimisation. For optimising both continuous variables and integer variables, the design problem is formulated as a mixed integer non-linear programming (MINLP) problem. A suitable optimisation framework using a stochastic algorithm is developed to solve this highly non-linear and constrained problem.

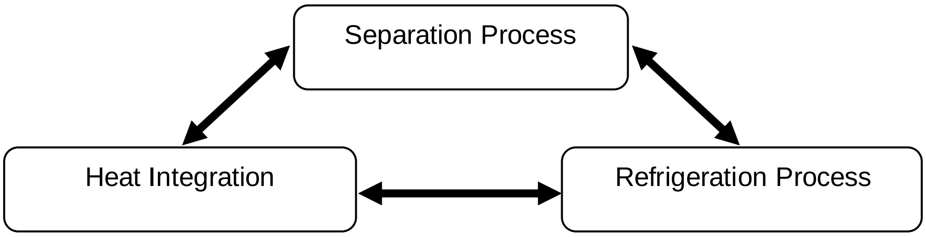


*Figure 3: Building blocks of low temperature plant*

## 3. Heat-integrated Sub-ambient Distillation

Distillation is also an important process for separating the components of gas mixtures such as the effluent of the reactor in an olefins process and gas processing. Separation of gas mixtures in olefins or gas processing not only has high energy consumption, but also demands expensive utility system at sub-ambient temperatures (Farrokhpanah, 2009).

For design of a separation process options include the order of separating the components, type of separation devices and their operating conditions. Cooling at temperatures below ambient temperature is provided by a refrigeration system. The refrigeration system absorbs heat by vaporisation of a low pressure refrigerant. The vaporised refrigerant is then compressed and condensed at a higher pressure against a cold utility or heat sink. Refrigerant compressors require power in order to increase the pressure of the vapour refrigerant. This mechanical energy is provided by steam turbines, gas turbines or electric motors, which, in turn, require thermal energy either directly or indirectly (e.g. electricity). High cooling demand of the separation process increases the power requirement in the refrigeration system.

There are important interactions between the refrigeration and separation systems that need to be exploited to maximize the integration opportunities. Studying the relevant processes results in the study of the building blocks of Figure 3 and their interactions.

A framework for synthesis of heat integrated sub-ambient separation sequences is needed that optimises key degrees of freedom in such processes simultaneously. Important design variables in the separation system, such as the separation sequence, type and operating conditions of the separation units (e.g. the operating pressure, feed quality and condenser type) need to be optimised simultaneously.

Moreover, the problem context is extended to heat integrated low temperature separation systems and optimises the important variables in the associated refrigeration system, at the same time as it optimises the degrees of freedom in the separation sequence. Various refrigeration provision strategies, such as expansion of a process stream, pure and mixed multistage refrigeration systems and cascades of multistage refrigeration cycles, are considered. The methodology optimises the key design variables in the refrigeration system, including the refrigerant composition, the number of compression stages, the refrigeration and rejection temperature levels, cascading strategy and the partition temperature in multistage cascaded refrigeration systems.

Even further, the methodology needs to exploit the interactions between the separation process and refrigeration system and develop heat integrated separation and refrigeration systems. The approach adopted in this work exploits a matrix based approach for assessing the heat integration potential of separation and refrigeration systems in the screening procedure. The approach also simulates and optimises heat pump assisted distillation columns to explore the heat integration opportunities through open loop heat pumping.

Another key aspect of separation sequence design is stream conditioning. In a separation sequence, stream conditioning is an important part of the process. The operating and capital cost for the process of preparing the feed can change considerably the economics of a design. The developed methodology simulates the feed and products coolers, heaters, compressors and expanders in a distillation sequence and includes their associated costs are in the overall cost of the process. Moreover, the feed quality to each column is optimised.

The approach adopted combines an enhanced simulated annealing algorithm with MILP optimisation method and develops a framework for simultaneously optimising different degrees of freedom in the heat integrated separation and refrigeration processes (Farrokhpanah, 2009).

## 4. Summary

Whilst the approach to the design of heat integrated distillation systems has traditionally been decomposed into the two sub problems of the distillation design and heat integration, it is now clear that a simultaneous approach is required. The approach requires a link between models of the distillation and heat exchanger network. For low-temperature systems operating with refrigeration is a utility, they are additionally needs to be a model of the refrigeration system linked to the model of the heat exchanger network (Farrokhpanah, 2009). Only in this way can the complex interactions be captured. This approach has been successfully applied to the classic problem of crude oil distillation design and optimisation. It has also been successfully applied to the design of sub ambient systems, such as ethylene production.

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